ANL-AFCI-163

Low Conversion Ratio Fuel Studies

prepared by
Nuclear Engineering Division
Argonne National Laboratory

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Objective and Scope

Recent studies on TRU disposition in fast reactors indicated viable reactor performance for a sodium cooled low conversion ratio reactor design. Additional studies have been initiated to refine the earlier work and consider the feasibility of alternate fuel forms such as nitride and oxide fuel (rather than metal fuel). These alternate fuel forms may have significant impacts upon the burner design and the safety behavior. The work performed thus far has focused on compiling the necessary fuel form property information and refinement of the physics models. For this limited project, the burner design and performance using nitride fuel will be assessed.

Highlights

Technical Summary

In November, 2005, Robert N. Hill and Micheal A. Smith traveled to LANL to discuss AFCI low conversion ratio fast reactor (LCFR) studies. In these studies, fuel enriched with recycled LWR TRU is used in a conventional fast reactor design for the purpose of TRU destruction. The focus of the meeting was to discuss the viable fuel forms and identify the set of data measurements being performed at LANL and INL that would be useful for the new work along with any existing data available at LANL which would be appropriate. The primary LANL contacts were Michael W. Cappiello, Stuart Maloy, Stewart Voit, and Eric Pitcher.

The initial part of the meeting involved a general discussion of the fuel forms which can potentially be used in LCFRs: metal, nitride, oxide, and carbide. The last of these was not initially considered a potential fuel form; however, recent developments in India seem to indicate that the fuel form should at least be considered. Some key properties of each fuel form are listed in Table 1, where it is understood that these properties are subject to change depending upon the composition and fabrication techniques along with irradiation induced effects. The overall purpose of the meeting was to initiate the compilation of fuel property (and performance) data of interest for the LCFR reactor.

The first discussion focused on any available data for metal fuel at the material content needed for LCFRs (30-60% TRU enriched heavy metal). As expected, neither side had significant data for the targeted fuel form, thus additional discussion on the effort required to obtain such data occurred. The overriding conclusion was that some of this data would be available from the ATR tests currently being performed at INL.

Table 1. Sample of Selected Fuel Material Properties

Fast Reactor Fuel Type Fresh Fuel Properties	Metal U-20Pu-10Zr	Oxide UO_2-20PuO_2	Nitride UN-20PuN	Carbide UC-20PuC
Heavy Metal Density, g/cm^3	14.1	**9.3**	13.1	12.4
Melting Temperature, ^{o}K	**1350**	3000	3035*	2575
Thermal Conductivity, W/cm-K	0.16	**0.023**	0.26	0.20
Operating Centerline Temperature at 40 kW/m, (T/T_{melt})	1060 (0.8)	2360 (0.8)	1000 **(0.3)**	1030 **(0.4)**
Fuel-Cladding Solidus, ^{o}K	**935**	1675	1400	1390
Thermal Expansion, 1/K	17E-6	12E-6	10E-6	12E-6
Heat Capacity, J/cm-K	0.17	0.34	0.26	0.26
Reactor Experience, Country	US, UK	RUS, FR, JAP US, UK		IND
Research & Testing, Country	US, JAP, ROK, CHI	RUS, FR, JAP, CHI	US, RUS, JAP	IND

The next discussion was on nitride fuel which was the primary topic of the meeting. Currently, LANL is fabricating and testing nitride fuel although not specifically for the LCFRs. Similar to metal fuels, the discussion dealt with possible LCFR nitride material contents and whether these compositions could be included in the ongoing work at LANL. On this point there was mutual agreement that data measurements could be taken, although there were outstanding problems with the fabrication of Am and Cm bearing nitrides. The existing library of information was quite lacking and the impact of irradiation remains to be considered. The discussions identified several issues for consideration in the design studies: 1) hydrogen contamination and 2) natural nitrogen versus enriched N-15 nitrogen.

A final discussion focused on the oxide fuel form and what data exits at LANL and ANL. As was the case for the preceding fuel forms, only sporadic data with limited or no irradiation behavior exists at the targeted content and enrichment. Given this, additional discussion focused on potential oxide fuel fabrication and measurement capabilities at LANL. The general conclusion was positive, but clearly the present work is fabricating and analyzing nitride fuel and thus this work was deferred for future exploration.

Additional discussions on different coolants indicated that more detailed data on lead coolant may be available from the ongoing work at LANL into lead and lead-bismuth corrosion studies. It was decided that with all of the preceding information, the work at ANL would be to focus on developing better fuel contents for the various fuel forms and coolants. This data will then be given to LANL for the purpose of fabrication and data measurement.

Subsequent to the milestone meeting, work was carried out to complete the three tables that follow for metal, oxide, and nitride fuel forms. The current metal and nitride fuel property tables using data accumulated by LANL and ANL, are given in Tables 2 and 3, respectively. The oxide fuel data obtained at ANL is summarized in Table 4. In the following tables, the black colored text indicates data which is well documented while text colored red indicates data based upon estimates and sparsely available data. Text colored blue indicates the research currently being carried out at LANL and INL.

Table 2. Available Physical Data for Metal Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Pu Enrich. Fuel (x,y,z) **x** U-**y** Pu-**z** Zr	(71,19,10) (w/o)	(36,43,21)	(~0,60,40) (0,100)
Theoretical Density (g/cc)	15.85	14.5	11.76 15.88
Smear Density †	0.75	0.75	0.75
Thermal Exp. (cm/cm·C)	(273-Melt.) for Unirradiated		
Axial Swelling	5%	5%	Zr/Pu fuel~ 20% @ 2 at. % burnup (973K)
Conductivity (W/m·K)	(273-Melt.) for Unirradiated		~20-25 (800-1000K)
Heat Capacity (J/kg·K)	(273-Melt.) for Unirradiated		~ 36 for d phase(J/Kmole)
Melting Temp. (K)	Generally Available		
TRU Fuel Form (v,w,x,y,z) **v**U-**w**Pu-**x**Am-**y**Np-**z**Zr	(24,20,3,1,52) (a/o)		
Theoretical Density (g/cc)	11.53		
Smear Density †	~66%		
Thermal Exp. (cm/cm·C)	Will be measured at INL		
Axial Swelling %	Will be measured after AFC irradiations		
Conductivity (W/m·K)	35-40 at 800-1000K		
Heat Capacity (J/kg·K)			
Melting Temp. (K)			

†Combination of fabricated density modification and volumetric adjustment

For metal fuel, a considerable amount of information exists for plutonium enrichments less than 10% with some data available up to 20% and sparse data up to 40%. As for enrichment with TRU there is very little information readily available, but the current work at LANL/INL should help fill in some of the required information. At high enrichment, some of the data is incomplete and the noted temperature ranges need to be compared to operating conditions. Furthermore, the impact of the fabrication technique and irradiation damage is not explicitly quantified.

There is not as much data present for nitride fuel as there is for metal. Consequently, nitride fuel is currently a focus of several experiments being carried out at LANL and INL. As can be seen for conventional enrichment, there is some data available which is appropriate for this work, but for medium and high enrichment fuels, data is relatively unavailable.

For oxide fuel, there is a significant amount of data present for plutonium enriched oxide fuel due to its use in LWR technology. However, the cladding is typically different in addition to the coolant considerations (water versus sodium) thus the direct application of this data is not straightforward. As for TRU enriched fuel or medium or high enriched plutonium data, very little data has been found although there are some indications that data may be present. As mentioned previously, experiments with oxide fuel at LANL/INL appear to be plausible, but they are not scheduled to be performed for this study, nor as part of the current AFCI research plans.

Table 3. Available Physical Data for Nitride Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Fuel Form (a,b,c,d) (**a**U-**b**Pu-cAm-dNp)N	(80,20,0,0) w/o	(50,25,15,10) a/o	(0,100,0,0)
Theoretical Density (g/cc)	14.32	14.22	14.25
Fabricated Density (g/cc)	13.17	80-94% theory.	~94% theory
Thermal Exp. (cm/cm·C)	500C-1500C coarse	Measured at INL	(500-1500C) F(C)
Axial Swelling	F(burnup) with considerable variability (1400-1650C)	Measured at INL after irradiation	Some Pointwise Data
Conductivity (W/m·K)	400K-1600K coarse	Measured at INL	1000-1200K
Heat Capacity (J/kg·K)	F(T) 20 K-1800 K	Measured at INL	1000-1200K
Melting Temp. (K)	3053 +/- 20 K		
Clad Chemical Limits			
Young's Modulus (GPa)	(100,0,0,0) as a F(porosity) (85,15,0,0) as a F(porosity)		
Poisson's Ratio	(100,0,0,0) as a F(porosity) (85,15,0,0) as a F(porosity)		
Fission Gas Release	(100,0,0,0) ~5% at 5 a/o burnup 1300K		

Table 4. Available Physical Data for Oxide Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Fuel Form (a,b,c,d) **a** $UO_{\mathbf{b}}$-**c** $PuO_{\mathbf{d}}$	(80,2,20,2) (w/o)		
Theoretical Density (g/cc)	~10.76 @ 1000K		
Smear Density †	0.75		
Thermal Exp. (cm/cm·C)	(273-1000)		
Axial Swelling			
Conductivity (W/m·K)	(273-1000)		
Heat Capacity (J/kg·K)	(273-1000)		
Melting Temp. (K)	Generally known		
Clad Chemical Limits	Quite a bit of data exists due to LWR technology		

†Combination of fabricated density modification and volumetric adjustment

Overall, although a significant amount of data does exist, but the accuracy of the different evaluations is unclear and the enrichment levels are not applicable to this study. Although this does raise serious issues with safety margins, it does not preclude the ability to perform reactor core calculations. With regard to this fact, we simplified the preceding data tables to indicate the quality and quantity of the data relevant to the modeling calculations (both safety and core performance) that need to be performed for design studies. For final design studies it is imperative to note that detailed measurements are required to reduce the uncertainty in all of the data once the fuel form is decided upon.

In the tables that follow we have made three basic categories: good, sufficient, and lacking. For the “good” category, the data exists in a state where the error due to material content or fabrication is minor with respect to the numerical modeling. For the “sufficient” category, the data is somewhat questionable or the numbers derived from that data are questionable, either of which would not result in a large uncertainty in the modeling calculations. For the “lacking” category, the data is very poor and can be expected to result in a large uncertainty in the modeling calculations. Those places left blank indicates that either no information has been found yet or none exists.

The physical data for metal fuel is summarized in Table 5 where the blue highlighted text indicates areas of improvement expected from the work at LANL/INL. As can be seen, the data is generally sufficient for the conventional enriched fuel and high enriched fuel. For medium enriched fuels, the data is simply not present. It is important to note that the medium enrichment fuel property data can be interpolated between the conventional and high enriched fuel. Such an approach would not properly account for fabrication differences or irradiation behavior, but it is a reasonable approach for the current stage of this work.

Table 5. Summary Table for Metal Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Pu Enriched Fuel			
Theoretical Density (g/cc)	Sufficient	Lacking	Sufficient
Smear Density †	Sufficient	Lacking	Lacking
Thermal Exp. (cm/cm·C)	Sufficient		
Axial Swelling	Sufficient		Sufficient
Conductivity (W/m·K)	Good		Sufficient
Heat Capacity (J/kg·K)	Good		Lacking
Melting Temp. (K)	Good		
TRU Enriched Fuel Form			
Theoretical Density (g/cc)	Lacking		
Smear Density †	Lacking		
Thermal Exp. (cm/cm·C)	Lacking		
Axial Swelling %	Lacking		
Conductivity (W/m·K)	Lacking		
Heat Capacity (J/kg·K)			
Melting Temp. (K)			

Table 6 summarizes the physical data for nitride fuel. As was the case for the metal fuel, the conventional and high enrichment fuels have some sufficient data but there are serious questions about fabrication details. In general, the measurements being performed at LANL and INL (highlighted in blue) would greatly improve the knowledge of this fuel form.

Table 6. Summary Table for Nitride Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Theoretical Density (g/cc)	Sufficient	Sufficient	Sufficient
Fabricated Density (g/cc)	Sufficient	Sufficient	Sufficient
Thermal Exp. (cm/cm·C)	Sufficient	Lacking	Sufficient
Axial Swelling	Lacking	Lacking	Lacking
Conductivity (W/m·K)	Lacking	Lacking	Lacking
Heat Capacity (J/kg·K)	Lacking	Lacking	Lacking
Melting Temp. (K)	Sufficient		
Clad Chemical Limits			
Young's Modulus (GPa)	Lacking		
Poisson's Ratio	Lacking		
Fission Gas Release	Lacking		

Table 7 summarizes the physical data for oxide fuel. As mentioned before, there is sufficient data for conventional enrichment, but its applicability to the current work is questionable.

Table 7. Summary Table for Oxide Fuel

	Conventional Enrichment (10-40)	**Medium Enrichment (40-60)**	**High Enrichment (60-100)**
Theoretical Density (g/cc)	Good		
Smear Density †	Good		
Thermal Exp. (cm/cm·C)	Good		
Axial Swelling	Good		
Conductivity (W/m·K)	Good		
Heat Capacity (J/kg·K)	Good		
Melting Temp. (K)	Good		
Clad Chemical Limits	Lacking		

†Combination of fabricated density modification and volumetric adjustment

In conclusion, there is sufficient data to perform design studies using either the explicit library data or data extrapolated from the existing data. This is a result of the fact that the design studies typically only need reasonable estimates of the fuel density and irradiation behavior (i.e. swelling). Although data extrapolation will obviously contain errors, the impact upon the core design should be minor. If conservative values are chosen, we can expect improvements in the data to generally result in improvements in the core design and performance rather than detrimental ones. Of course, using such data in detailed thermal and safety evaluations is generally unacceptable, hence the need for physical data measurements.